Chapter 1

Mesoscale Modeling

1.1 A brief historical perspective

The first comprehensive mesoscale studies on Earth addressed meteorological hazards at regional scales mostly through two-dimensional idealized modeling: e.g, tropical hurricanes [Anthes et al., 1971] and mountain meteorology [Mahrer and Pielke, 1977]. Those idealized numerical tools formed the basis for modeling studies of mesoscale atmospheric disturbances in the Martian atmosphere, with a particular emphasis on slope winds [Ye et al., 1990, Savijärvi and Siili, 1993] and orographic waves [Pickersgill and Hunt, 1981, Tobie et al., 2003].

In the 1980's and beyond, a more unified approach was adopted in terrestrial studies. The modeling efforts were pursued to build platforms capable of reproducing the mesoscale variability in any region of the world at various horizontal scales [Pielke et al., 1992, Dudhia, 1993, Skamarock and Klemp, 2008]. Those efforts yield the versatile three-dimensional mesoscale models used nowadays in operational weather prediction and meteorogical research. This progress in terrestrial mesoscale modeling, along with an unprecedented harvest of new observations, some of which related to phenomena left unresolved by global circulation models [GCMs], motivated the development of dedicated three-dimensional mesoscale models for the Martian atmosphere [Rafkin et al., 2001, Tyler et al., 2002, Toigo and Richardson, 2002, Siili et al., 2006, Wing and Austin, 2006, Richardson et al., 2007, Spiga and Forget, 2009].

Meteorological models aiming at resolving mesoscale phenomena share similar structure and design as GCMs described in chapter **??**. They comprise two main modules:

1. the *dynamical core* integrates primitive equations for the atmospheric fluid, i.e. Navier-Stokes equations projected on the rotating frame using spherical coordinates.

2. the *physical parameterizations* compute

    - key diabatic forcing in the primitive equations: radiative transfer, surface-atmosphere heat exchanges, latent heat release.

    - unresolved dynamical phenomena with the chosen grid spacing: friction, boundary layer mixing, wave breaking.

Despite this common framework, crucial differences can be reported between GCMs and mesoscale models. In what follow, mesoscale models would be described through those main differences with GCMs.

1.2 Dynamical core

A major difference between GCMs and mesoscale dynamical cores is related to the assumption of hydrostatic equilibrium. The hydrostatic equilibrium consists in retaining gravity only as being responsible for vertical stratification of pressure:

$$\frac{\partial p}{\partial z} = -\rho g \tag{1.1}$$

with altitude z, pressure p, acceleration of gravity g and density ρ. An alternative formulation for hydrostaticity is obtained through integrating this equation between two atmospheric levels z_1 and z_2

$$p_1 - p_2 = -\int_{z_1}^{z_2} \rho\, g\, dz \tag{1.2}$$

where pressure then naturally arises as an equivalent for atmospheric mass.

Hydrostatic equilibrium is only strictly true for a static atmosphere, devoid of any horizontal pressure gradients, which is not the case of a real atmosphere (as can be inferred from e.g. geostrophic equilibrium). Notwithstanding this, dimensional analysis and observations show that, for most meteorological phenomena occurring at spatial scales larger than ~ 10 km, gravity force and vertical pressure gradient remain the two most prominent terms in the vertical component of primitive atmospheric equations. In other words, hydrostatic equilibrium stands as a correct approximation as long as acceleration of vertical wind $\frac{dw}{dt}$ is negligible compared to acceleration of gravity g. To illustrate this, Janjic et al. [2001] proposed a simple equation based on the distinction between "true" pressure P_s, as measured by a barometer at the surface, and hydrostatic pressure p_s, which verifies hydrostatic equilibrium :

$$P_s = p_s + \int_0^1 \epsilon\, p\, d\sigma' \quad \text{with} \quad \epsilon = \frac{1}{g}\frac{dw}{dt} \tag{1.3}$$

where σ' denotes a convenient vertical coordinate which definition is not essential here. As long as vertical accelerations in the atmosphere are low or inhibited, e.g. when atmospheric stability is particularly high, the hydrostatic equilibrium is valid.

Given the low vertical velocities involved in large-scale atmospheric phenomena, hydrostatic equilibrium can be assumed in primitive equations used for GCMs computations. While hydrostaticity is still fairly common amongst regional-scale phenomena, mesoscale atmospheric dynamics possibly involve strong vertical acceleration (convective updrafts, gravity waves, ...) causing the atmospheric state to depart from hydrostatic equilibrium. Hence the equation for vertical motions is usually implemented in its complete version in mesoscale models. The importance of non-hydrostatic effects can be further exemplified by mesoscale gravity waves, associated to the buoyancy restoring force: the

dispersion relation between wave frequency ω and spatial wavenumber (k, l, m) writes

$$\omega^2 = f^2 + N^2 \, \frac{k^2 + l^2}{m^2} \tag{1.4}$$

under hydrostatic assumption, but writes

$$\omega^2 = f^2 \, \frac{m^2}{k^2 + l^2 + m^2} + N^2 \, \frac{k^2 + l^2}{k^2 + l^2 + m^2} \tag{1.5}$$

with all non-hydrostatic contributions [see Fritts and Alexander, 2003, f is Coriolis parameter and N is atmospheric stability]. In other words, hydrostatic integration left an important part of the gravity wave spectrum unresolved: mesoscale studies devoted to resolving gravity wave phenomena must be based on non-hydrostatic models.

There is another important difference between GCM and mesoscale dynamical cores, which is specific to Mars. An intercomparison of Martian mesoscale models carried out in 2003 revealed that non-hydrostatic models had significantly overestimated the diurnal surface pressure cycle compared to hydrostatic models [Tyler and Barnes, 2005]. The origin of the problem was the diabatic heating terms in the pressure tendency equation being neglected in non-hydrostatic dynamical cores used for Martian applications [Dudhia, 1993]. This approximation yields negligible differences on Earth, but not on Mars, leading to the aforementioned overestimation of the thermal tides signatures. A solution, which has been implemented in most mesoscale models since, is to include the fully compressible equations in the model: the pressure tendency equation is replaced by the equivalent, though much simpler, geopotential equation in which the diabatic heating is included [Spiga and Forget, 2009].

1.3 Physical parameterizations

Mesoscale models usually rely on the same state-of-the-art physical parameterisations of dust, CO_2 and H_2O cycles developed in Martian GCMs: the MRAMS model developed by Rafkin et al. [2001] and the OSU MM5 model developed by Tyler et al. [2002] are based on NASA Ames GCM radiative transfer and soil model [Pollack et al., 1990]; the Cornell MM5 developped by Toigo and Richardson [2002] is based on physics of the GFDL model described in Wilson and Hamilton [1996]; the LMD mesoscale model developed by Spiga and Forget [2009] is interfaced with the complete physical packages designed for the LMD GCM [Forget et al., 1999]. Of key importance for the Martian climate, the spatial and temporal variations of dust opacity are usually prescribed in mesoscale model similarly to GCM and derived from 1999-2001 Thermal Emission Spectrometer measurements [Smith et al., 2001], thought to be representative of Martian atmospheric conditions outside of planet-encircling dust storm events [Montabone et al., 2006].

The main differences in physical parameterizations between GCMs and mesoscale are of two distinct kind:

1. Some physical parameterizations inherited from GCMs for unresolved dynamical processes are unsuitable for mesoscale modeling simply because these dynamical processes are resolved by mesoscale modeling and no

longer in need to be approximatively accounted for. For instance, gravity waves are not resolved in GCMs but these could induce a drag on the large-scale circulation when they break. This impact on the large-scale circulation through momentum transport is parameterized in GCMs by taking into account topographical wave sources enclosed within a GCM grid box [Miller et al., 1989, Lott and Miller, 1997]. In mesoscale simulations, the topographical field is described with horizontal resolutions from tens of kilometers to hundreds of meters, hence the gravity-wave drag scheme can be switched off. Note that the boundary between what is resolved and what is parameterized is often uncertain, especially in intermediate scales between mesoscale and microscale phenomena, known as the "grey zone" or "Terra Incognitae" [Wyngaard, 2004].

2. New physical parameterizations must be added specifically for mesoscale applications. For instance, mesoscale models resolve steeper topographical contrasts than GCMs, hence the need to account for sloping terrains in the radiation scheme [Rafkin et al., 2002]. It was shown that terrestrial parameterizations, where the solar irradiance reaching an inclined surface is deduced from the value in the horizontal case, can be modified / generalized to Mars-like dusty atmospheres and easily included in mesoscale models [Spiga and Forget, 2008].

Mesoscale modeling also highlighted that, when GCMs and mesoscale models share a given similar physical parameterization, the latter are sometimes more suitable than the former to detect limitations to this parameterization. This is e.g. the case for convective adjustment. This parameterization modify any unstable layer with negative potential temperature gradients (an usual near-surface situation during Martian afternoons) into a neutral equivalent [Hourdin et al., 1993]. It is necessary for the sake of numerical stability and physical consistency to include such parameterization in GCMs and mesoscale models because circulations prone to turn the unstable layer into a neutral layer are not resolved in both types of models (see **??** for further details). Notwithstanding this, as pointed out by Rafkin [2003], the use of such an artificial convective adjustment scheme might be questionable in Martian atmospheric models. Convective adjustment leads to a significant underestimation of both near-surface temperatures and winds in the afternoon: mesoscale modeling carried out in Chryse Planitia by Spiga and Forget [2009] showed that, when convective adjustment is removed, the modeled diurnal variations of near-surface temperature and winds are more consistent with observed variations by Viking and Pathfinder. Yet switching off convective adjustment yields new problems: in the afternoon, near-surface temperatures are overestimated and spurious vertical motions might appear in the boundary layer. Similar diagnostics in terrestrial studies lead to develop "thermal models" [Siebesma and Cuijpers, 1995] which are now planned to be used in Martian conditions, where convective plumes responsible for boundary layer mixing are particularly strong (see chapter **??**).

1.4 Initial and boundary conditions

While GCMs integrate the geophysical primitive equations on the whole sphere, the vast majority of mesoscale modeling for the terrestrial and Martian atmo-

sphere make use of limited-area strategy. In other words, computations are carried out in a specific region of interest on the planet. An adapted map projection is defined for the chosen region of computation: e.g. stereographic projections are used for polar regions [Tyler and Barnes, 2005] (which actually ensures that mesoscale simulations are devoid of any pole singularity, an usual drawback of GCMs that requires the use of additional filtering). Another approach to resolve mesoscale phenomena is to run GCMs at higher resolution than usual or use adaptable-grid zooming capabilities [Moudden and McConnell, 2005, Richardson et al., 2007, Spiga and Lewis, 2010]. This approach is presently not prominent in mesoscale modeling studies, owing to computational limitations which allows to reach resolutions no finer than several $\sim$ 10s km contrary to limited-area models. This is likely to change in the near-future due to increase in computational power.

In limited-area modeling, horizontal boundary conditions for winds, temperature and advected tracers, have to be provided during the simulations in addition to an atmospheric starting state. Note that this is not needed in idealized simulations which usually require the use of periodic, symmetric or open boundary conditions. In "real-case" simulations, the specified boundary conditions and the atmospheric starting state are derived from previously performed GCM simulations which have reached equilibrium, typically after $\sim$ 10 simulated years. A relaxation zone of a few grid points width is implemented at the boundaries of the mesoscale domain to enable both the influence of the large-scale fields on the limited area and the development of the specific mesoscale circulation inside the domain. In Martian conditions, GCM fields are usually in need to be updated every one or two Martian hour to constrain the mesoscale model at the domain boundaries. This is significantly more often than large-scale updates in the terrestrial case (closer to 6 hours) and is deemed necessary by the presence of strong thermal tide perturbations on Mars, as first noticed by Tyler et al. [2002]. Another key element in boundary conditions yielding optimal downscaling in the limited-area domain is the consistency in physical parameterizations between the "bounding" GCM and the associated mesoscale model [Spiga and Forget, 2009].

Dimitrijevic and Laprise [2005] showed that using only one mesoscale domain constrained on its boundary by GCM results yields unbiased results when the boundary forcing involves a minimum of $\sim 8-10$ GCM grid points [possibly lower in situations of complex topography, as shown in Antic et al., 2006]. Hence the single-domain approach is only suitable for mesoscale simulations of horizontal resolution of $dx \sim$ 10s km. To reach finer horizontal resolutions of few kilometers in mesoscale simulations, nested domains must be employed [as first introduced in numerical studies of terrestrial fronts, see Harrison and Elsberry, 1972]. Nested mesoscale simulations make use of more than one limited-area domain where meteorological fields are computed:

- the parent domain which features large geographical extent, coarse horizontal resolution and specified boundary conditions by GCM results;
- one or several domains of smaller extent and finer grid resolution, centered in a particular zone of interest and "nested" into the parent domain which provides boundary conditions.

Using a parent domain sufficiently extended over the planet is necessary to

correctly represent thermal tides and planetary waves (e.g. Kelvin, Rossby waves). Thus far, nested simulations are used in most existing mesoscale models for the Martian atmosphere [Rafkin et al., 2001, Tyler et al., 2002, Spiga and Forget, 2009].

Vertical boundaries (bottom and top of the model) are treated in mesoscale modeling rather similarly as in GCMs. Two notable differences can be mentioned for the top boundary. Firstly, absorbing ("sponge") layers at the model top have to be stronger in mesoscale models because a much larger part of the gravity-wave spectrum is resolved and yield large temperature and wind disturbances at higher altitudes. Secondly, mesoscale simulations are usually carried out with lower model top ($\sim 40-50$ km) than GCMs, which could adversely affect large-scale circulations such as the upper branch of Hadley circulation [Toigo and Richardson, 2002, Spiga and Forget, 2009]; thus far, mesoscale modeling have thus mostly addressed Martian meteorological phenomena below 40 km altitude. One possible solution is to specify boundary conditions derived from GCM results also at the model top [Rafkin et al., 2001]. As far as the surface boundary is concerned, topography is usually taken into account in the dynamical core through calculating a surface geopotential. Surface thermophysical properties (albedo, thermal inertia) intended for mesoscale computations are extracted from high-resolution maps derived from recent spacecraft measurements, mostly on board Mars Global Surveyor.

In the process of initialization and definition of boundary conditions, the vertical interpolation of GCM meteorological fields to the terrain-following mesoscale levels must be treated with caution. While deriving the near-surface meteorological fields from GCM inputs, one may address the problem of underlying topographical structures at fine mesoscale horizontal resolution, e.g., a deep crater that is not resolved in the coarse GCM case. A crude extrapolation of the near-surface GCM fields to the mesoscale levels is usually acceptable for terrestrial applications. On Mars, owing to the low density and heat capacity of the Martian atmosphere, the surface temperature is to first order controlled by radiative equilibrium, and thus it is left relatively unaffected by variations of topography [e.g., Nayvelt et al., 1997]. A practical consequence, which renders an extrapolation strategy particularly wrong on Mars, is that the near-surface temperature and wind fields vary much more with the distance from the surface than with the absolute altitude above the areoid (or equivalently with the pressure level).

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